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Dynamic Heat Production Modeling for Life Cycle Assessment of Insulation in Danish Residential Buildings

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Abstract

Residential building insulation is regarded as an easy solution for environmentally friendly building design. This assumption is based on the perception that the amount of thermal energy used to create insulation in most cases is much smaller than the amount of thermal energy that is needed for space heating without insulation over the lifespan of a building. When the energy sources for insulation production are similar to the energy mix that supplies heat, this logic is valid to very high level of insulation. However, in Denmark, as well as many other countries this assumption is becoming increasingly incorrect. Given the generally long service life of buildings, the significance of future energy mixes, which are expected/intended to have a smaller environmental impact, can be great. In this paper, a reference house is used to assess the life cycle environmental impacts of mineral wool insulation in a Danish single-family detached home. This single family house, is based on averages of current Danish construction practices with building heat losses estimated using Be10. To simulate a changing district heating grid mix, heat supply fuel sources are modeled according to Danish energy mix reports of fuel mix since 1972. Both the dynamic impact potentials saved by using insulation and the impacts induced from insulations production are utilized to create an overall dynamic energy inventory for the life cycle assessment. Our study shows that the use of such a dynamic energy inventory is necessary for for increasing the validity of optimization assessment, and our study further shows that it is likely that current Danish regulation will not promote optimum levels of insulation in the near future.

Peer-review under responsibility of the organizing committee of SBE16.

Keywords: Sustainability Assessment; Building Insulation; Energy Systems; Life Cycle Assessment

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1. Introduction

Residential building insulation has long been a subject of interest when energy savings are being discussed. Of the massive amounts of energy that are used in the residential sector, a considerable fraction is spent on space heating. For example, in Denmark, the average household uses 71.2 GJ of energy per year, of which nearly 83% are used for space and water heating[1]. Issues such as energy consumption in households have led many researchers and innovators to look at the production of 'net-zero' or 'passive' buildings. Realizing that the environmental impacts, and cost, of insulation might be important when assessing an entire home, some have gone further to look at the energy balance[2] or life cycle cost optimization[3] of insulation, suggesting that balances and optimizations might be a better indicator of ideal insulation levels. Some have even gone all the way by creating a comparative life cycle assessment of various insulation levels used in buildings[4]. While these assessments thoroughly cover the potential energy/environmental and economic issues faced in optimizing a building's energy performance, they do not adequately address the probably most significant issue; energy system dynamics. When approaching the issue of projecting environmental impact into the future, already published assessment do not account for the dynamic nature of energy mixes used for heating of buildings and thus fail to account for the changing (over time) environmental impacts from energy provision to buildings.

In many places, such as Denmark, the makeup of the energy system has changed significantly over the last decades following a trend toward more efficient and environmentally friendly energy production, and it is likely that changes will continue to occur in the energy supply that provides heat to residential buildings going into the future[5]. This dynamic energy supply for buildings means that the environmental impacts of heating a house will change over time, while the impact of insulation, which is set at the time of construction, remains static. Looking at this relationship, with the environmental impact of insulation amortized over the life of a building, an environmental impact development curve can be established, describing the development of the environmental impacts resulting from the heating of a building over time. When both dynamic and static energy scenario environmental impact curves are plotted, the comparison between the impacts of an assumed static energy mix and the reduction in environmental impacts due to improvements in the energy mix is easily seen (Figure 1 A). This approach for location of the energy break-even point can be further developed into a comparison of insulation levels where an insulation system optimized based on a static energy mix compared to a system that is optimized based on a dynamic energy mix (Figure 1 B).

In order to understand the break-even issue, a reference house representing an average Danish single family home using two insulation scenarios IS2015 and IS2020 is compared. These insulation scenarios are based on regulatory levels in the Danish Building code, and are intended to be indicative of insulation levels found in a well insulated standard single family home and a super-insulated near 'net-zero' single family home.

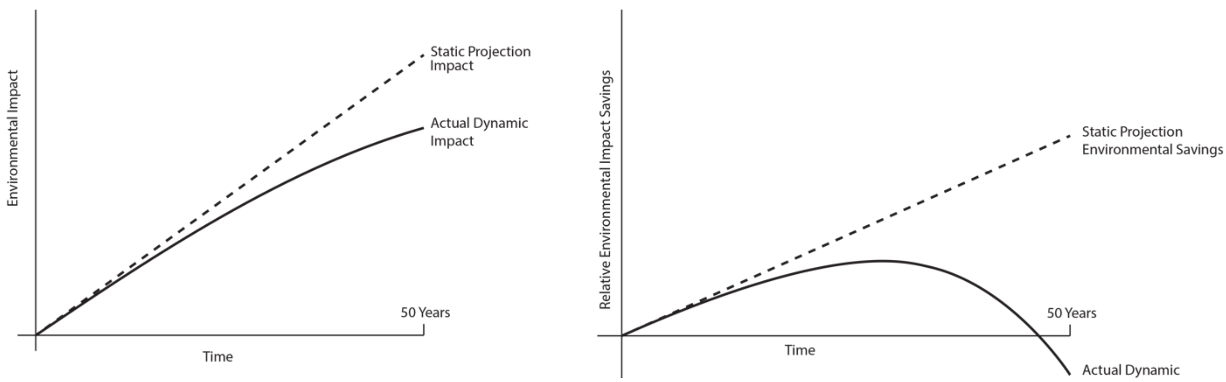


Figure 1: A. Hypothesized static energy mix environmental impact projection and dynamic energy mix comparison B. Hypothesized relative impact of an insulation scenario optimized for static energy scenario projection versus a lower level of insulation shown with both static energy system projected savings and actual environmental impact due to dynamics in the energy supply.

IS2015	Insulation Scenario, designed to meet Danish BR10 Low Energy 2015 regulations for energy loss
IS2020	Insulation Scenario, designed to meet Danish BR10 Building Class 2020 regulations for energy loss
LCA	Life Cycle Assessment
BR10	Danish building regulations 2010, valid until 30 June, 2016 when they will be replaced by BR15

2. Methodology

The goal of this study is to compare the environmental impacts of a well-insulated home with the impacts of a super-insulated home while proposing that the use of a dynamic energy mix is necessary for more exact modeling optimized insulation levels. Our study is intended to create a better understanding of the larger synergies present in the development of sustainable building practices that reach beyond the construction and design sectors. To that end, the impact of differing levels of insulation and shifts in energy supply are quantified through a life cycle assessment of a standard Danish single family home with the functional unit of ‘a single detached house heated for 50 years’. It is assumed that the service life of a single-family house is 50 years, but due to the presence of only 42 years of energy data, the impacts of construction materials are amortized over the 50-year service life and reapplied on an annualized basis for comparison to heat supply impacts. As this study is intended to show a generalized pattern rather than specifics of a certain production for the purpose of product comparison, European processes were chosen from an existing database to be appropriate for general application in policy making.

In this study, only marginal impacts associated with a range of insulation scenarios are assessed. Because of this, all other building materials, etc. not affected by the changing insulation thickness are ignored, as they are the same in both scenarios. The system boundary is defined as shown in (Figure 2). All processes use allocation at the point of substitution. It is further assumed that many of the consequences of varying levels insulation, such as the varying amounts of energy and minor materials needs for building construction, are more complex than shown here, but such analysis is outside the scope of this project.

A building energy use model was developed to quantify the essential incremental construction materials and heat necessary in a given insulation scenario. While the goal of this study is to be as generally applicable as possible, the shape, typology, etc. of a building have a significant ability to affect the outcome of energy use simulations as they directly change factors such as exterior envelope to interior area ratios, window to wall area ratio, etc., which have a determining influence on the efficiency of a building envelope. With regard to the influence building design can have on the outcome of our study and in order to make the results generally applicable, a representative house design was

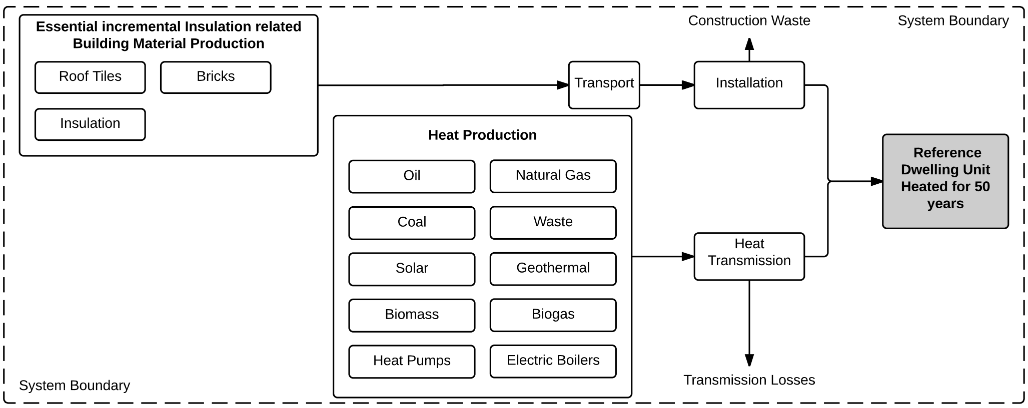


Figure 2: System boundary and flows for LCA comparing IS2015 and IS2020

used for the modelling of energy loss. Our model, based on a Danish Building Institute reference house design[6], represents an average construction of a single family home in Denmark. It is a rectangular plan with a hip roof and lightweight concrete filled cavity walls, further specifications are outlined in Table 1. To test multiple levels of insulation, a building heat loss model was created using BE10, a building energy use modelling software, which was developed by the Danish Building Institute to demonstrate that the energy requirements of the Danish building regulations, BR10, and other laws are followed. Because of its inherent link to regulation, this software was deemed ideal for the assessment of heat losses for the purposes of this study. The input U-values and other factors used for this model are listed in Table 1 and Table 2.

Table 1: Reference house details

Building Component	Description
Foundation/floor	Light Concrete Slab with insulation on grade, wood flooring with plywood underlay, and filled masonry block foundation with a linear loss of 0.12 W/mK. 151.2 m^2 gross heated floor area.
Windows	High performance double pane argon filled, with low-e coating. Overall U-value (W/m^2*K), including frame and mullions, of 1.0. Total glazed area including frames and mullions 35.8 m^2.
Walls	Aerated concrete cavity walls with 100mm of concrete, a brick façade, and varying levels of mineral wool cavity insulation. Total exterior wall area of 125.4 m^2.
Roof	Hip roof with masonry tiles, plywood sheathing, varying levels of mineral wool cavity insulation.
Ventilation	Mechanical heat recovery ventilation at 0.3 l/s per m^2 with 85% efficient heat recovery

2.1. Reference house insulation scenarios

To test the impact of a changing energy supply on the net environmental impact, two insulation scenarios were developed. These scenarios represent two politically relevant levels of insulation. The first, IS2015 is based on the low-energy building class in the Danish building regulations BR10[7]. IS2015 represents a very well insulated building, and it is a required level of building performance for Danish homes beginning 30 June, 2016. The second insulation scenario, IS2020, was developed to meet the 2020 building class as outlined in BR10. This house represents a super-insulated class of houses, near to the insulation level of a passive house. It is developed such that it would attain passive house classification with the inclusion of a small solar panel installation or similar. The insulation thicknesses and associated whole building element U-values (W/m^2*K) used to obtain energy losses meeting these requirements are outlined in Table 2.

Table 2: Insulation scenario insulation levels and associated U-values

Insulation thicknesses (mm) for insulation scenarios	**IS 2015**	**IS 2020**	**U-Values for associated insulation thicknesses**	**IS 2015**	**IS 2020**
Wall	350	550	Wall	0.104	0.069
Roof	575	875	Roof	0.066	0.044
Floor	450	650	Floor	0.073	0.052
*Based on BE10 calculations			**Annual Heat Requirement (mWh)***	2.14	1.44
**Based on EPD declared 41 kg/m^3 (Rockwool)			**Insulation Mass (ton)****	9.3	14.5
			ReCiPe single score impact factor	5.66E+04	8.85E+04

For the calculation of lifetime impact of the insulation scenarios, Europe relevant Ecoinvent 3.2[8] processes were used in OpenLCA for packaged rock wool, as well as necessary marginal brick façade material and clay roof tiles. All materials are assumed to be transported 200km, and the lifetime impacts are amortized over a 50-year lifespan, allowing annual impact to be established using ReCiPe single score heirarchist characterization.

2.2. Heat production

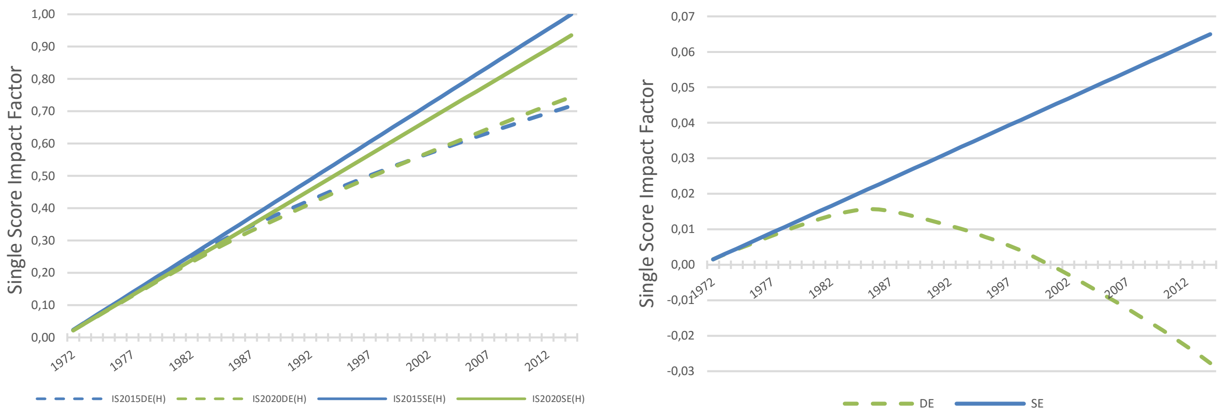
In order to quantify the balance of the potential for climate change from a dynamic energy mix, endpoint impact values were calculated for each heat production type that is used to make up the district heating system (Table 3). These values were calculated using European processes from Ecoinvent 3.2 in OpenLCA. Total energy mix impact per unit of energy was calculated by summing the impacts of the ten energy production types multiplied by their respective proportion of the energy mix, as reported by the Danish Energy Agency[9] on an annual basis using ReCiPe single score heirarchist characterization. For the Static energy mix, the proportions for 1972 were used for all years.

Table 3: ReCiPe Single score impact factor by production type for 1mWh of delivered energy and development of energy mix 1972-2012

	Biogas	biomass	coal	Electric boilers	geothermal	heat pumps	natural gas	oil	solar	Waste
Single score impact (Hierarchist)	0.00E+00	1.05E+02	1.26E+03	1.57E+03	6.90E+02	9.58E+02	2.57E+02	1.41E+03	2.24E+02	0.00E+00
Energy mix by year	Biogas	biomass	coal	Electric boilers	geothermal	heat pumps	natural gas	Oil	solar	Waste
1972	0.02%	0.06%	2.28%	0.00%	0.00%	0.00%	0.00%	88.06%	0.00%	9.58%
1977	0.02%	0.31%	8.93%	0.00%	0.00%	0.00%	0.00%	78.16%	0.00%	12.58%
1982	0.02%	0.86%	25.31%	0.00%	0.00%	0.00%	0.00%	58.46%	0.00%	15.34%
1987	0.08%	7.57%	41.49%	0.00%	0.00%	0.00%	18.66%	15.91%	0.00%	16.30%
1992	0.18%	12.92%	44.93%	0.00%	0.06%	0.00%	19.33%	4.13%	0.01%	18.45%
1997	0.60%	12.95%	34.30%	0.04%	0.06%	0.04%	24.66%	6.21%	0.02%	21.11%
2002	0.77%	14.95%	24.24%	0.06%	0.11%	0.01%	30.47%	6.04%	0.05%	23.30%
2007	0.90%	22.79%	21.92%	0.11%	0.38%	0.01%	28.14%	4.39%	0.07%	21.28%
2012	0.97%	33.20%	17.93%	0.75%	0.32%	0.02%	26.38%	2.74%	0.39%	17.30%

3. Results

From the Life Cycle Assessment results, an annual progression of the aggregated environmental impacts was established. The static energy scenario for a house built in 1972 shows a clear preference for the IS2020 insulation scenario (Figure 3 A). However, when the dynamic energy supply scenario was applied, IS2020 resulted in a greater overall impact than IS2015 (Figure 3 B). These results confirm the development impacts throughout the use phase of the life cycle of a building as hypothesized (Figure 1). All impact values were internally normalized to 1 for final comparison, with 1 representing greatest impact through division by greatest value.



A. **B.**

Figure 3: Life Cycle Assessment with ReCiPe Hierarchist single score impact factor values based on internal normalization through division by maximum value. **A.** Comparison of IS 2015 and 2020 Static and dynamic insulation scenarios total impact. **B.** IS2020 static and dynamic energy scenario impact savings compared with IS2015, negative values indicate that IS2020 has a greater cumulative impact

4. Discussion and Conclusions

As hypothesized in Figure 1, our results indicate that the difference between SE and DE mixes is a determining factor in the selection of an optimal insulation level for a single family home. This understanding is crucial for promoting effective building insulation and energy performance regulations. While it is impossible to know with absolute certainty what will happen to the energy supply over the lifespan of a building when it is constructed, depending on the location, there are likely plans or projections in place that could help guide the determination of impact for future energy mixes. The development shown throughout the lifespan of the reference house in this study indicates that the use of projections with a moderate to high level of certainty is likely more valid than static input for evaluation of energy use impacts in in relation to assessment of a building's life cycle environmental impacts. While the results presented in our paper using aggregated single score indicators are significantly more uncertain than other impact assessment methods and do not allow for comparison outside of this study, such as a multi-variate analysis of midpoint impacts might, the results of this study are meant to be indicative of a problem in current assessment method rather than an indicator of the absolute impacts of a single scenario.

The overall findings from this study indicate that using the proposed method of dynamic energy mix input in a life cycle assessment of Danish homes, instead of a static heat mix is preferable because future energy mix projection are readily available and have a fair degree of certainty[10]. Using such a method, it would be possible to check the overall impacts of the current building regulations given the political goals that the Danish Energy Agency has laid out for its future energy supply[10]. The results of this study also demonstrate that it is very likely that the current Danish building regulations will not promote the most environmentally friendly or healthy construction methods in 2020, assuming that mineral wool manufacture methods do not change before then.

Though it was not done in this study, primarily due to the small scale of this paper, a life cycle assessment of single family home insulation assessing a wider range of insulation scenarios using a projected-future dynamic energy supply to allow for assessment of new construction should be completed to ensure that the regulations promote healthy and environmentally friendly design. Along with such a study, a multivariate analysis of midpoint impacts should be completed in order to reduce uncertainty and avoid missing locally relevant environmental and health related impacts from any given scenario. And, while the the reference house and energy mix used in this study to represent the Danish market is gives a good indication of optimal levels of insulation for construction of Danish single family homes, the optimal insulation levels should not be construed as indicative for other markets. However, the methods applied in this paper could be adapted to other smaller-national or regional markets to improve the effectiveness their respective building regulations.

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